Final Report

ONR Grant N66604-05-1-2983

Cooperative Autonomous Mobile Robots

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1 Objectives of the Research

The primary objective of the work was to develop new capabilities for cooperative autonomous operation of multi-agent autonomous mobile robot systems. Many vital Navy missions require autonomous navigation and decision making in complex, unstructured, and dynamic environments. In this work, we set out to develop software for cooperative autonomy and to test these algorithms on new, low-cost autonomous surface craft (ASC). The ASC were operated in several major ONR experiments, including AUVFest in June, 2005 and the FAF 05 experiment in July, 2005. Lessons learned from cooperative operation of these platforms can pay dividends for a wide variety of Navy research programs.

2 Technical Approach

The technical approach for this work had two components: (1) the SCOUT (Surface Craft for Oceanographic and Undersea Testing) autonomous surface craft, and (2) the MOOS (Mission Oriented Operating Suite).

2.1 Hardware

While several other researchers have performed experiments with an individual ASC [9, 4, 5], we believe that ASCs offer extremely powerful capabilities when operated together in mobile vehicle networks. The use of an ASC network for cooperative AUV research is akin to using training wheels to ride a bike; GPS and WiFi communications greatly ease software development for tasks such as formation-keeping and cooperative position estimation. The cost, complexity, and risk of these experiments are at least an order of magnitude less than similar experiments would be with AUVs. GPS measurements also provide a convenient ground truth for the trajectory estimation process.

The SCOUT ASC is fully described in Curcio et al. [2].

2.2 Software

One of the great practical challenges in robotics and AUV research is the issue of software. AUVs are very complex systems and the software to control them has historically been time-consuming and expensive to develop and difficult to maintain. To help us realize the ambition of autonomous navigation and mapping running in real-time on an AUV, we have created a completely new multi-vehicle operating system, called the mission-oriented operating suite (MOOS), that greatly simplifies the process of operating multiple autonomous vehicles. MOOS has been successfully tested on a very wide range of autonomous vehicles,

including Autonomous Surface Craft, an Odyssey II AUV, two Odyssey III AUV, and more than a dozen different land robots.

MOOS is the brain-child of Dr. Paul Newman, a postdoctoral research associate working in Prof. Leonard's research group under previous ONR and NOAA support. Recently, MOOS has been transitioned to be distributed under a GPL open source license. The use of MOOS both within MIT and internationally for both research and education is becoming widespread. The latest information about MOOS can be obtained at:

`http://www.robots.ox.ac.uk/~pnewman/MOOS/`

3   Project Accomplishments

Under the work on the present project, tools were developed to demonstrate cooperative operation of multiple SCOUTs running MOOS. The ASC were operated in several major ONR experiments, including AUVFest in June, 2005 and the FAF 05 experiment in July, 2005. Lessons learned from cooperative operation of these platforms can pay dividends for a wide variety of Navy research programs.

In the project we developed extensions to MOOS to enable cooperative positioning of the multiple SCOUTs and we also made some hardware and operational improvements on the SCOUT vehicles to make it easier to perform cooperative experiments with multiple vehicles.

The best description for our results is conveyed by the following figures which demonstrate the cooperative operation of the SCOUT platforms for a variety of experiments. See Figures 1 through 5 and the attached powerpoint presentation for a summary of our demonstrated capabilities.

Some of our experiments were performed in close collaboration with Dr. Michael Benjamin of NUWC, resulting in technology transfer from MIT to the Navy. This collaboration has grown substantially since the completion of the research, resulting in numerous joint publications, including:

- M. Benjamin, J. Curcio, J. Leonard, and P. Newman. A Method for Protocol-Based Collision Avoidance Between Autonomous Marine Surface Craft. *Journal of Field Robotics*, 23(5), pages 333-346, April, 2006.

- D. P. Eickstedt, M. R. Benjamin, H. Schmidt, and J. J. Leonard. Adaptive Tracking of Underwater Targets with Autonomous Sensor Networks. Accepted for publication in *Journal of Underwater Acoustics*, 2006. **

- M. Benjamin, J. Curcio, J. Leonard, P. Newman. Navigation of Unmanned Marine Vehicles in Accordance with the Rules of the Road. In *Proceedings of the IEEE International Conference on Robotics and Automation*, pages 3581-3587, May, 2006.

- D. Eickstedt, M. Benjamin, H. Schmidt, and J. Leonard. Adaptive Control of Heterogeneous Marine Sensor Platforms in an Autonomous Sensor Network. In *Proceedings of the International Conference on Robots and Systems*, Beijing, China, October, 2006. **

Therefore, the funded research was quite successful for cultivating collaboration between MIT and NUWC.

References

[1] J. Catipovic. Performance limitations in underwater acoustic telemetry. *IEEE J. Ocean Engineering*, 15(3):205–216, July 1990.

[2] J. Curcio, J. Leonard, and A. Patrikalakis. SCOUT — a low cost autonomous surface platform for research in cooperative autonomy. In *IEEE Oceans*, 2005.

[3] D. B. Kilfoyle and A. B. Baggeroer. The current state-of-the-art in underwater acoustic telemetry. *IEEE J. Ocean Engineering*, 25(1):4–27, 2000.

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[8] J. Vaganay, J. G. Bellingham, and J. J. Leonard. Outlier rejection for autonomous acoustic navigation. In *Proc. IEEE Int. Conf. Robotics and Automation*, pages 2174–2181, April 1996.

[9] T Vaneck, C. Rodriguez-Ortiz, M. Schmidt, and J. Manley. Automated bathymetry using an autonomous surface craft. *Navigation: Journal of the Institute of Navigation*, 43(4), 1996.

[10] L. Whitcomb, D. Yoerger, H. Singh, and Jonathan Howland. Advances in underwater robot vehicles for deep ocean exploration: navigation, control, and survey operations. In D Koditschek and J. Hollerbach, editors, *Robotics Research: The Ninth International Symposium*, Snowbird, Utah, 2000. Springer Verlag.

Figure 1: The MIT SCOUT Autonomous Surface Craft.

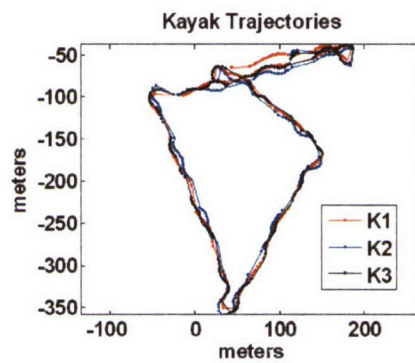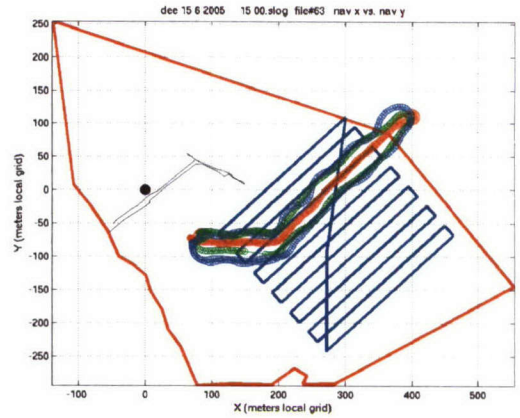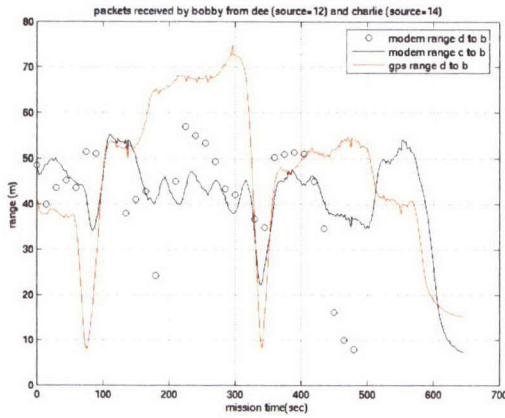Figure 2: Cooperative operation of several SCOUT ASCs.

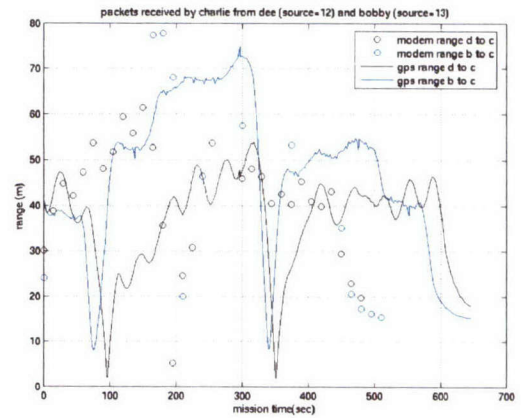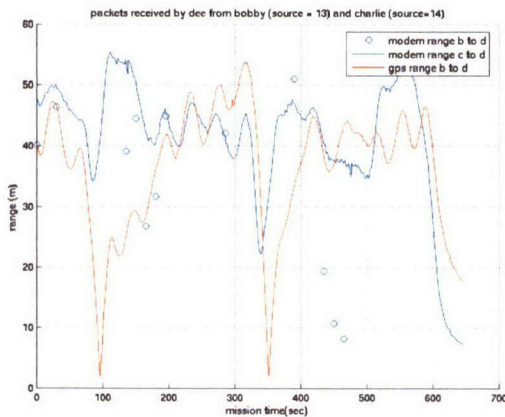Figure 3: Vehicle trajectories for a typical follow-the-leader missions.

(a)

(b)

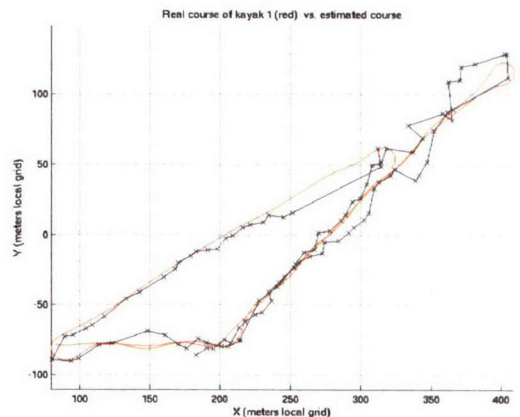

(c)

(d)

(e)

(f)

Figure 4: One-way Acoustic ranging results for three kayaks performing cooperative formation-keeping missions at AUVFest 2005 in Keyport, Washington. (a) MIT Scout AUVs performing cooperative formation keeping and acoustic ranging at AUVFest in Keyport, WA, in June 2005. (b) vehicle trajectories (from GPS). (c)-(e) absolute range errors for one-way acoustic ranging measurements for the three Scouts (Bobby, Charlie, and Dee). (f) MLBL computed vehicle trajectory for the lead kayak using GPS positions for the other two vehicles and one-way acoustic ranges.
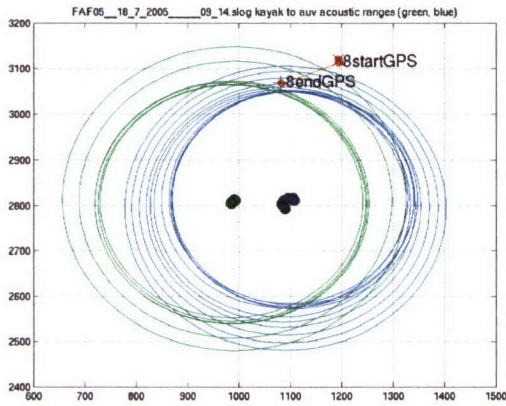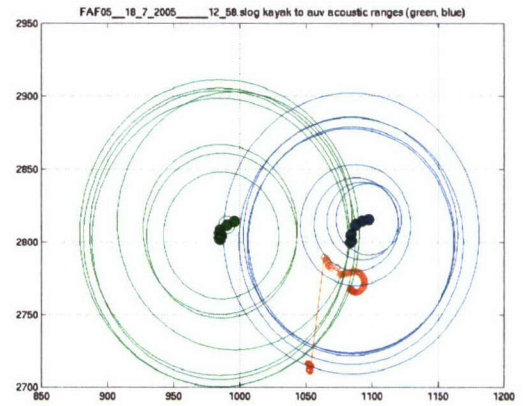
(a)
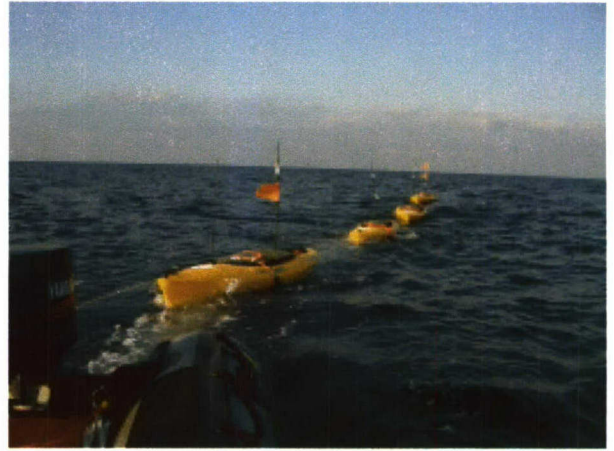
(b)

(c)

(d)

(e)

(f)

Figure 5: Deployment of four MIT Scout ASCs and two Odyssey IIIs at the Focused Acoustic Field (FAF) 2005 experiment in Italy. (a) Four Scouts and two Odyssey IIIs after shipment. (b) Four Scouts in tow to operations site at which four-AUV one-way-ranging and data transfer experiments were performed. (c) A Scout vehicle being launched from NATO R/V LEONARDO. (d) The Odyssey III AUV Unicorn and one of the MIT Scouts during joint AUV/ASC operations at FAF-05. (e)-(f) One-way acoustic range measurements displayed as circles referenced to the center of each of the Scout vehicles (blue and green circles) for two short missions (two minutes and six minutes respectively). GPS measurements of the AUV position at the start and end of the mission are shown as red circles.

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MIT Dept. of Mechanical Engineering   MIT Computer Science & Artificial Intelligence Laboratory
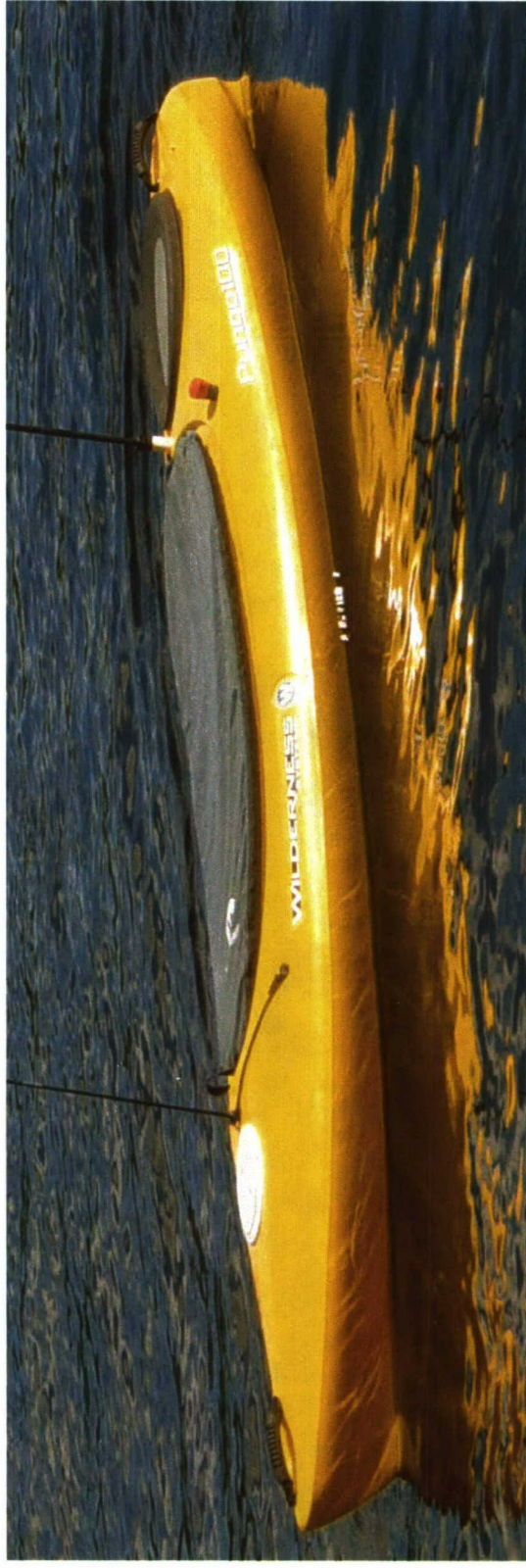
SCOUT Autonomous Surface Craft

Motivation:

- Low-cost reconfigurable platform for development and testing of cooperative autonomous algorithms
- Off-the shelf components for extremely low cost
- Flexible design enabling rapid addition of new sensors

Core components:
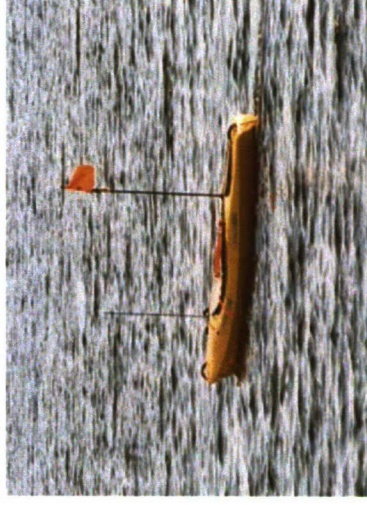
- GPS, R/C, RF Modem, 802.11b, MOOS operating system

SCOUT Autonomous Surface Craft
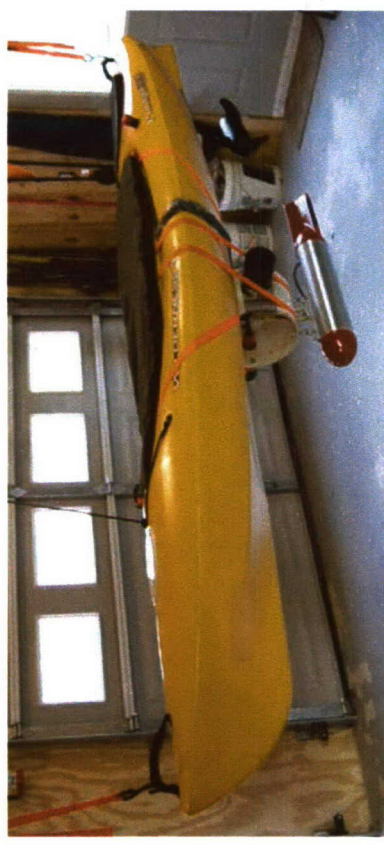
Specifications:

- HDPE Hull
- LOA: 10'
- Beam: 30"
- 12v 100AH

- Max Spd: 5 KTS
- Cruise Spd: 3 KTS
- Duration: 8 Hr
- GVW: ~200 LB

Configurations

- Multi vehicle cooperative behavior.
- Moving baseline navigation (using WHOI Modems).
- Side Scan Sonar
- Undersea Persistent Surveillance (UPS)

AUVFest Deployment (Keyport, WA, June 05)

Goals:

- **Moving baseline navigation data acquisition using WHOI modems**
  - ☐ Collaboration with Bluefin Robotics and WHOI
  - ☐ Other Sponsor: ONR AOFNC CNA/USS

- **Cooperative autonomy algorithm development**
  - ☐ Adaptive sensor network providing an ultra-wideband aperture for cooperative tracking
  - ☐ Other Sponsors: ONR UPS, ASAP MURI, and GOATS

# NUWC Keyport Operations Site

MIT Dept. of Mechanical Engineering

MIT Computer Science & Artificial Intelligence Laboratory

Autonomous Multiple Vehicle Operations

packets received by dee from bobby (source = 13) and charlie (source 14)

- modem range b to d
- modem range c to d
- gps range b to d
- gps range c to d

mission time(sec)

range (m)

dee 15 8 2005   14 20.slog file#81   nav x vs. nav y

X (meters local grid)

Y (meters local grid)

Autonomous Multiple Vehicle Operations

MIT Computer Science & Artificial Intelligence Laboratory

MIT Dept. of Mechanical Engineering
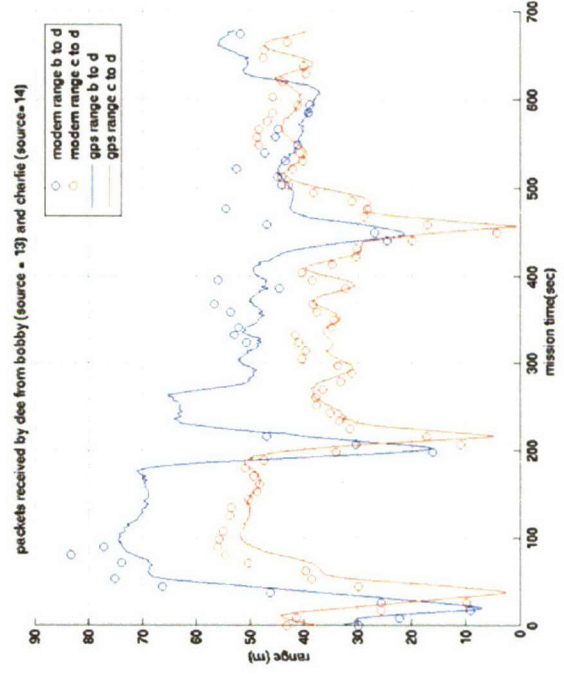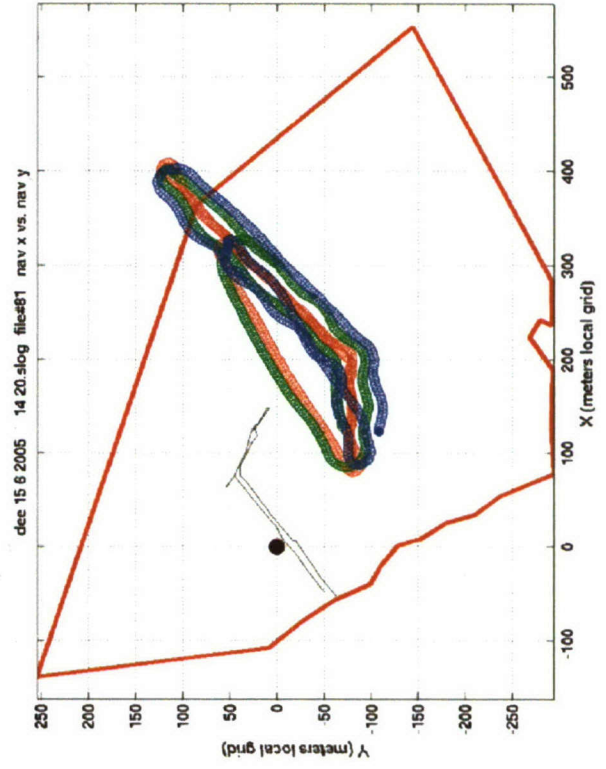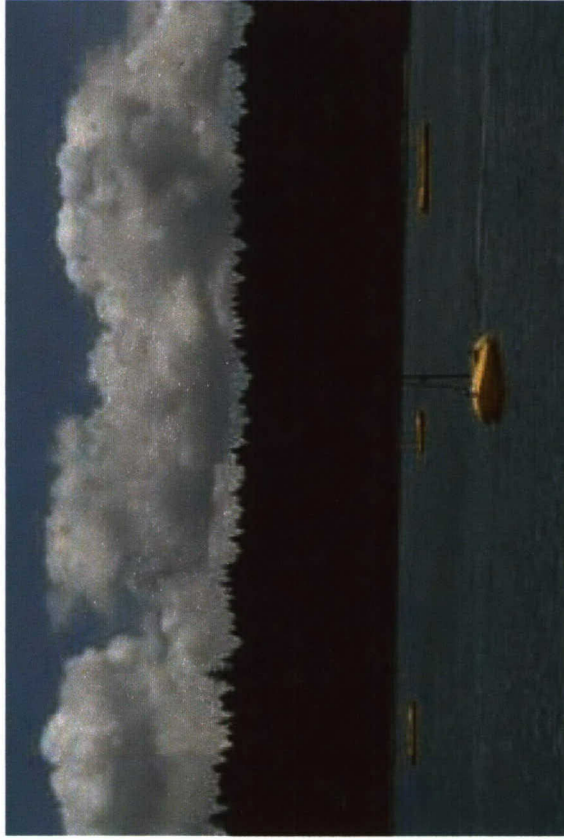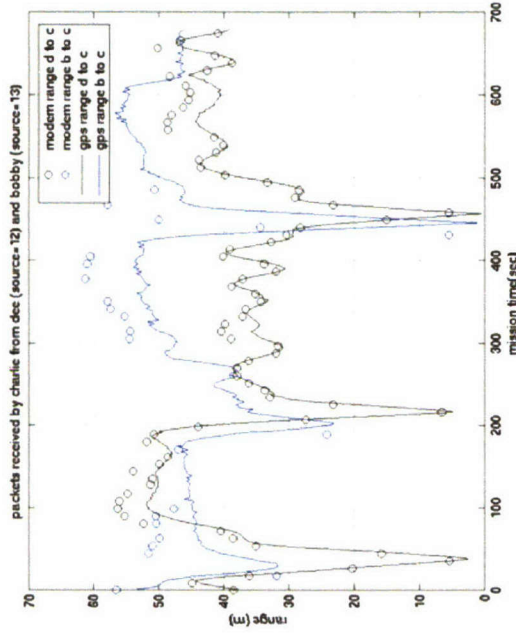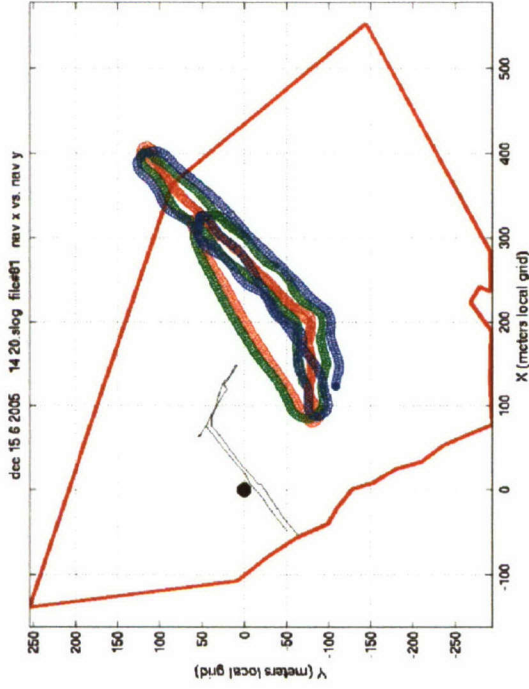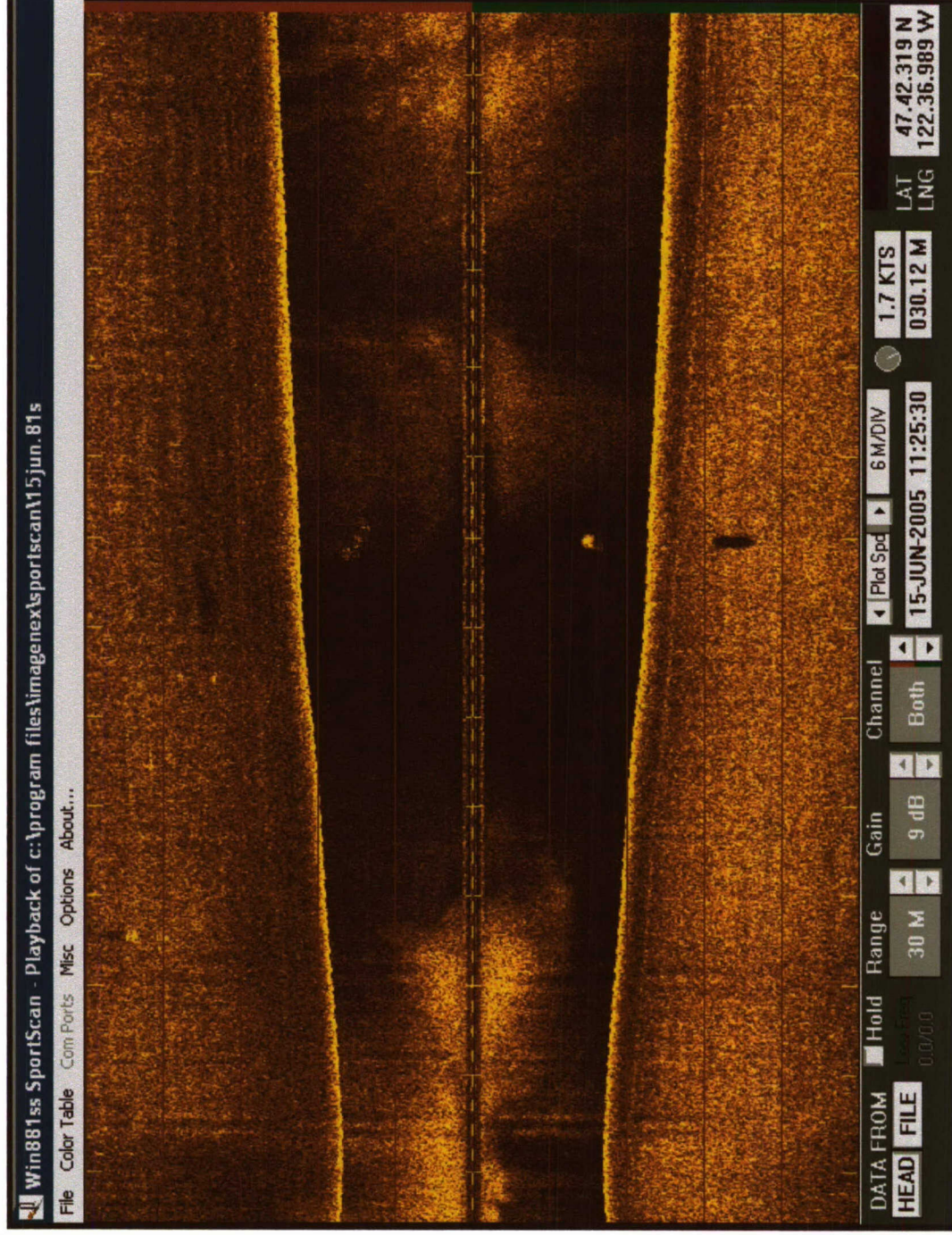
Cooperative Navigation Data Acquisition using WHOI microModems
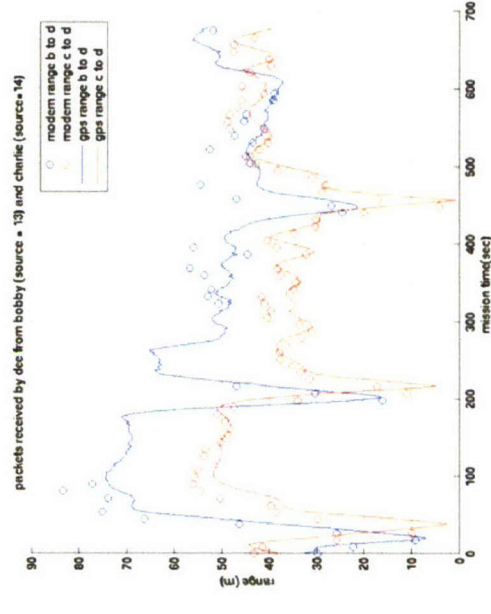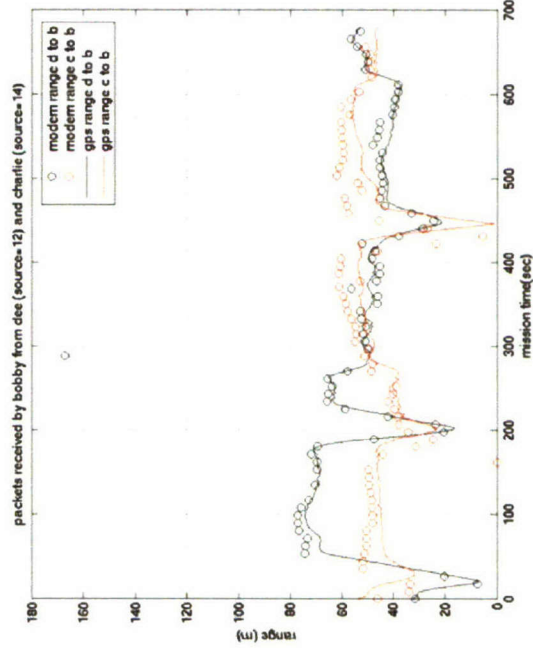
Autonomous Sidescan Sonar Data Acquisition with low-cost Imagenex Sportscan Sonar


Mission along side pier

MIT Computer Science & Artificial Intelligence Laboratory

MLO image acquired with sidescan sonar

Win881ss SportScan - Playback of c:\program files\images\nextsportscan\15jun.81s

File   Color Table   Com Ports   Misc   Options   About...

| DATA FROM | Hold | Range | Gain | Channel | | Plot Spd ▲ | 6 M/DIV | 1.7 KTS | LAT | 47.42.319 N |
| HEAD FILE | 0.0/0 | 30 M | 9 dB | Both | | 15-JUN-2005 11:25:30 | | 030.12 M | LNG | 122.36.989 W |

Mission near Nekton practice target

MIT Computer **S**cience & **A**rtificial Intelligence Laboratory

Autonomous Sidescan Sonar Data Acquisition
Real-time display of sonar on shore

MIT Computer Science & Artificial Intelligence Laboratory

MIT Dept. of Mechanical Engineering
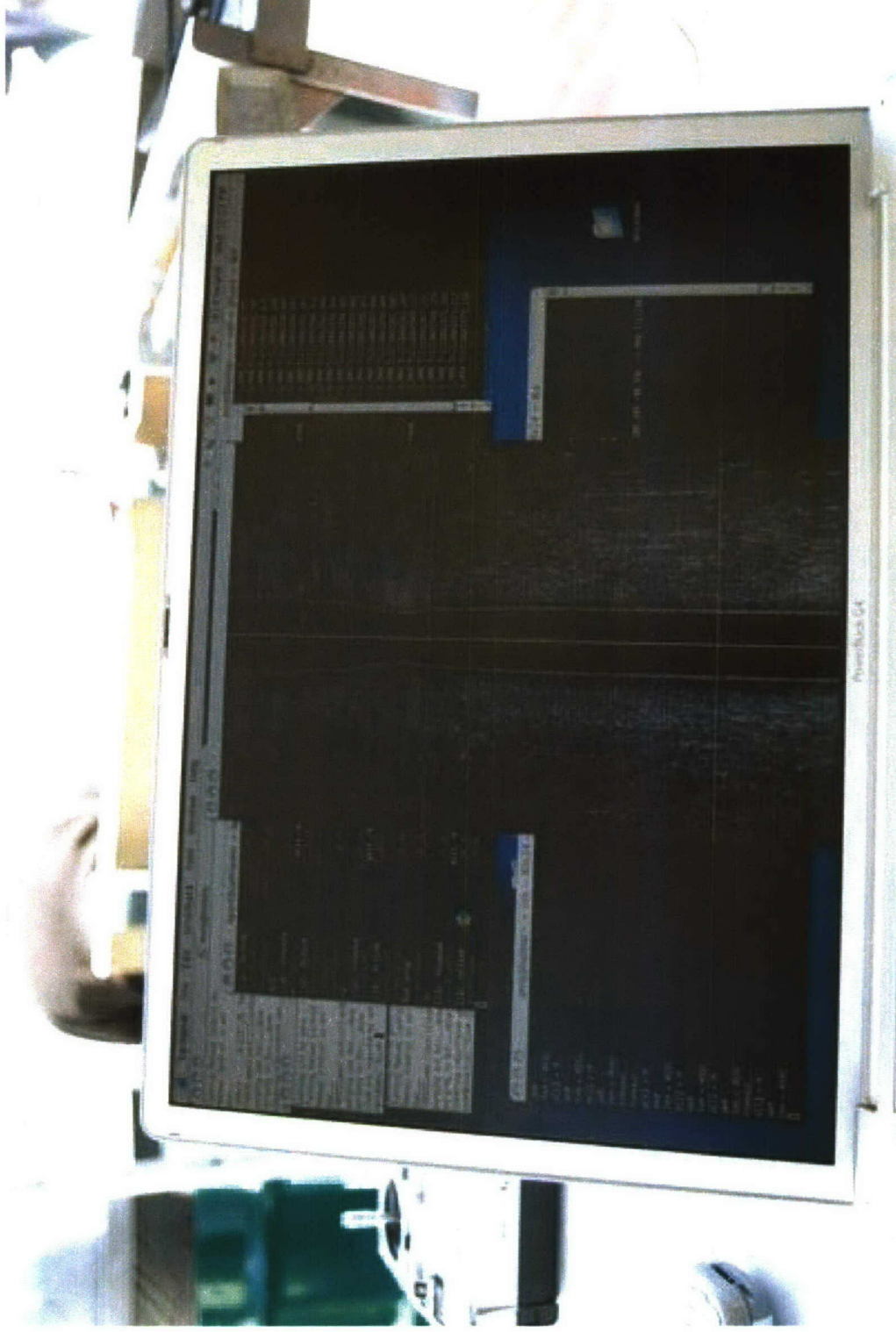
Charles River Experiments -- performed in Collaboration with M. Benjamin of NU

Charles River Experiments -- performed in Collaboration with M. Benjamin of NUWC

Deploying a Sensor Field with 6 Vehicles, Simulation Nov 14th 2005
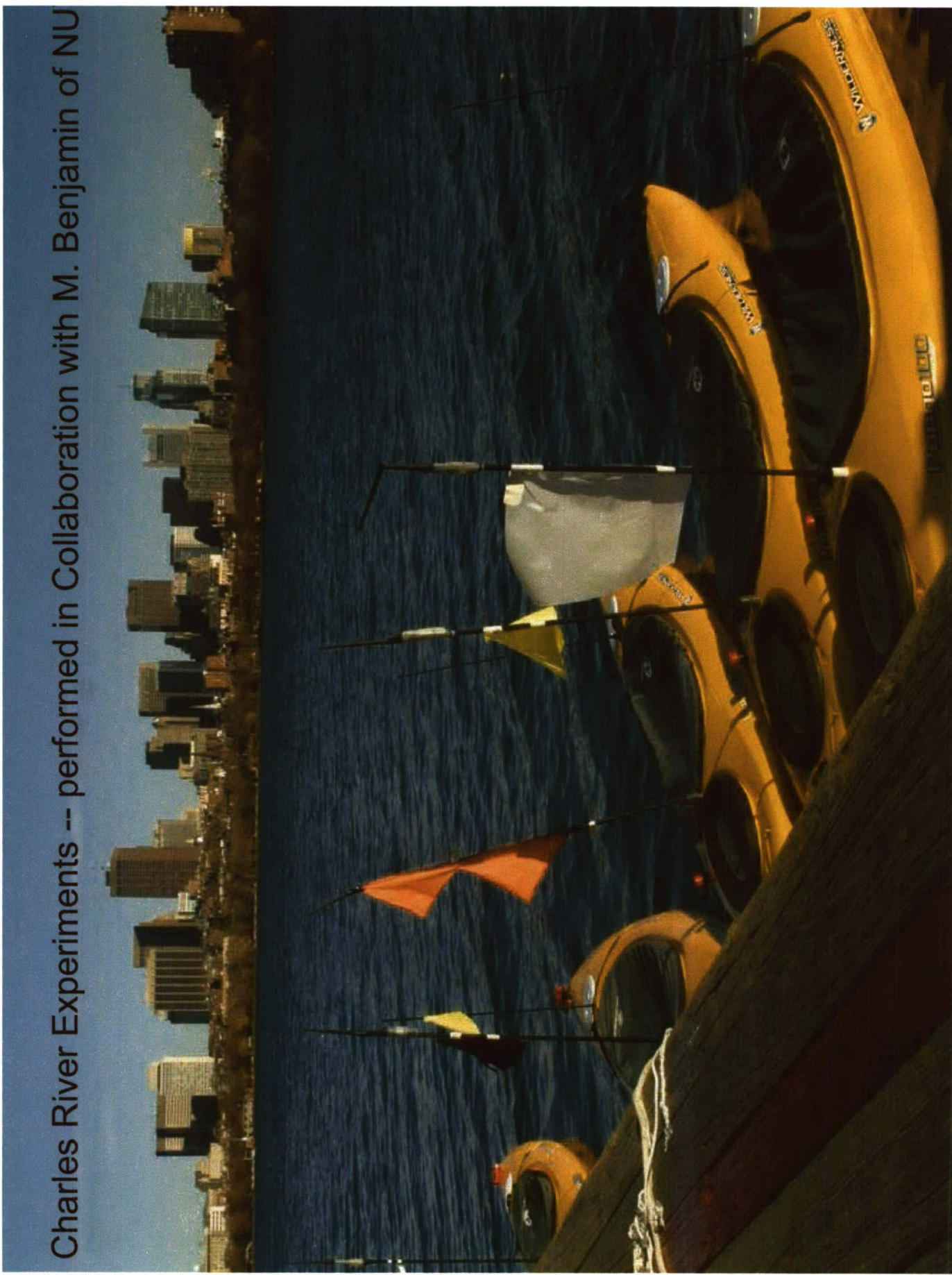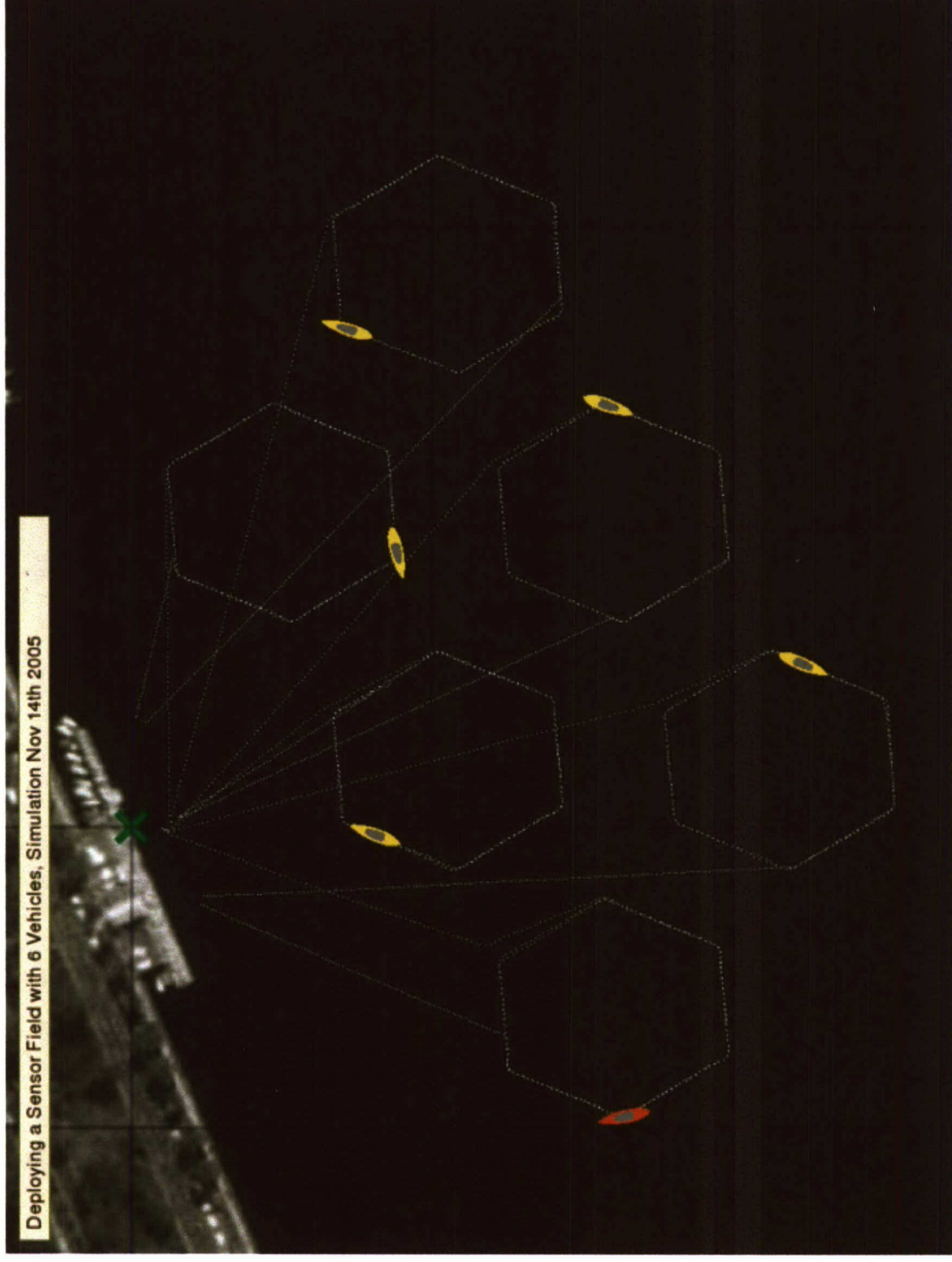
Simulated Cooperative Navigation

Joint work with M. Benjamin

Joint work with M. Benjamin